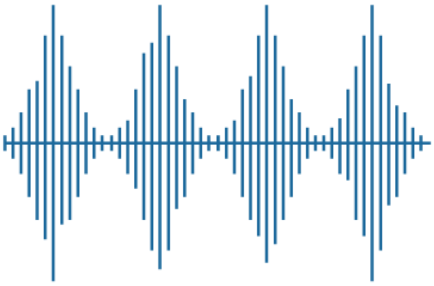
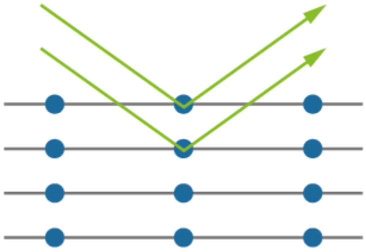
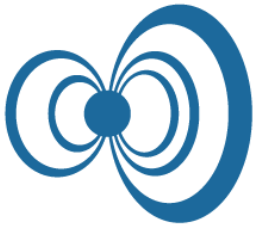






STRESSTECH BULLETIN 12

Measurement Methods of Residual Stresses

There are many methods to measure residual stresses. The methods are commonly grouped as non-destructive, semi-destructive and destructive or diffraction based, strain relaxation based and other methods. However, they all have the same common point: being indirect. There is no direct method available to measure stresses: they are calculated or derived from a measured quantity such as elastic strain or displacement.

Text: Murat Deveci, Figures: Stresstech

DIFFRACTION BASED METHODS

In diffraction based methods, the elastic strain is measured using Bragg's law and calculation of the stress is done with Hooke's law together with elastic modulus (E) and Poisson's ratio (ν).

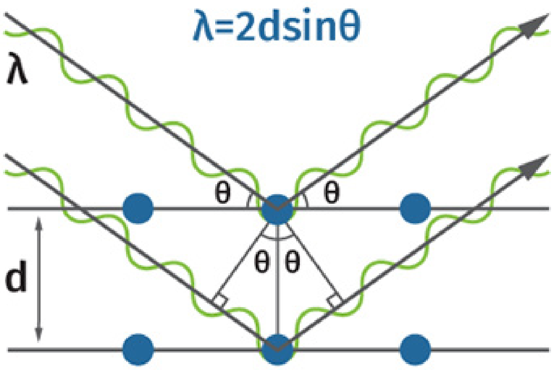


Illustration of the Bragg's law which describes X-ray diffraction from crystal lattice planes

Bragg's law describes X-ray diffraction from crystal lattice planes. In a stressed material, the wavelength of the X-ray (λ) is known, the distance between atomic planes (d) is unknown and the diffractions are observed at angles (θ). Stress causes small changes in d and shifts the diffraction angle. Bragg's law assumes incoming and diffracted waves to be in phase and undergoing constructive interference.

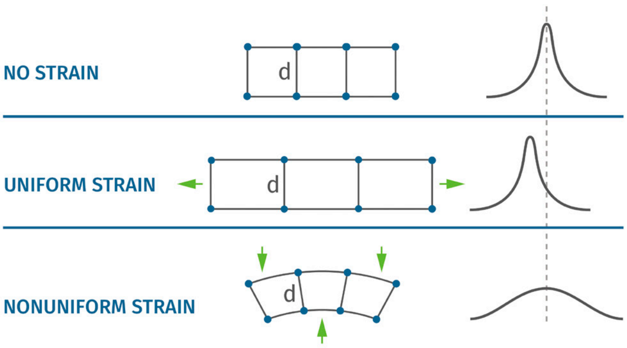
Residual stresses are determined from the diffraction data by calculating the strain from the diffraction peak positions. Any stress, including applied or residual stresses, induces a strain which corresponds to changes in lattice spacing. In practice, a metal powder with no stress is measured first to set the angular scale of the detectors for a certain material. Stress is then calculated by measuring lattice distance with multiple tilt angles and plotting the results as d vs. $\sin^2\chi$ graph, where d is the measured lattice spacing and χ is the tilt angle.

The residual stresses can be determined from the slope of this d vs. $\sin^2\chi$ graph. Measurements are usually fast, lasting from seconds to few minutes. Irradiated area size affects the measurement time; using a larger collimator reduces the needed time to make measurements.

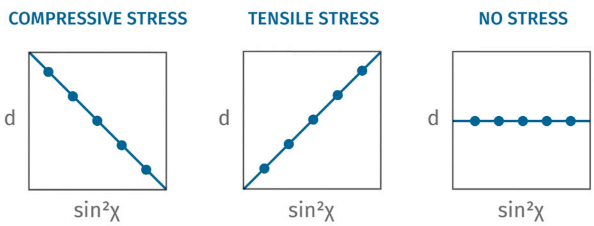
Stress calculation is affected by material-based parameters such as differences in lattice parameters, precipitations, interstitial occupation, and micro stresses. In a poly-crystalline structure with disordered crystals at the grain boundaries, precipitations and lattice defects, the diffraction line widens and forms a Gaussian-like peak.

The width of the peak is measured as Full Width at Half Maximum (FWHM) which illustrates micro stresses and/or hardness and plastic deformation; typically, value increases with increasing hardness.

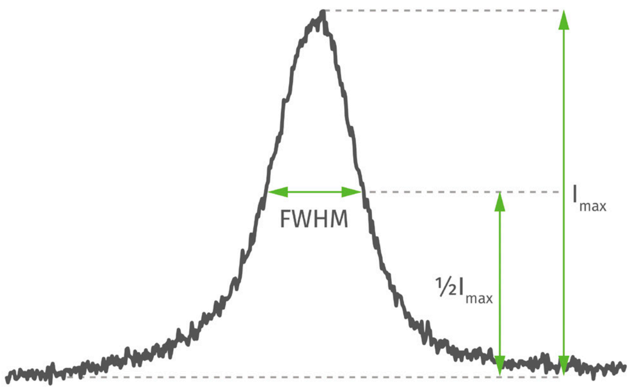
Uniform strain shifts the diffraction peak. Non-uniform strain can alter both the peak shape and position.



Residual stresses are determined from the diffraction data by calculating the strain from the diffraction peak positions.



The width of the diffracted peak is affected by micro stresses and imperfections in the crystal structure (i.e. dislocations, plastic deformation, etc.).



Residual Stress Measurement by X-ray Diffraction

X-ray diffraction (XRD) is a well-established and accurate method to investigate the residual stress levels on the surface layers of crystalline materials. X-ray diffraction for residual stress measurements is relatively cost-effective and widely available with portable and robotic diffractometers for both on-site and laboratory testing. XRD measurement is useful for stress analysis when the following conditions are met:

- ✓ Material must have a crystalline structure
- ✓ Material should have small grains
- ✓ Material elastic constant needs to be known

Non-destructive measurement depth for steel and aluminium is few to tens of micrometres below the surface. However, residual stresses are rarely completely described by a surface measurement alone. As an example, shot peening generates a residual stress state that varies with depth. To completely characterize the generated residual stress depth profile electro-polishing is used to expose a new surface to be measured. By using electro-polishing and successive measurements an analysis depth down to 1 mm can be reached. With the combination of grinding and electropolishing, the analysis depth can be extended down to 5 mm.

Relevant Standards for XRD

ASTM E2860 - 12 Standard Test Method for Residual Stress Measurement by X-Ray Diffraction for Bearing Steels

ASTM E915 - 16 Standard Test Method for Verifying the Alignment of X-Ray Diffraction Instrumentation for Residual Stress Measurement

ASTM E1426 - 14 Standard Test Method for Determining the X-Ray Elastic Constants for Use in the Measurement of Residual Stress Using X-Ray Diffraction Techniques

BS EN 15305:2008 Non-destructive testing. Test method for residual stress analysis by X-ray diffraction

A National Measurement Good Practice Guide, Determination of Residual Stresses by X-ray Diffraction – Issue 2, National Physical Laboratory, UK

Residual Stress Measurement with Neutron Diffraction

Neutron diffraction (ND) provides full residual stress tensor, σ11 (parallel to surface), σ22 (parallel to surface) and σ33 (normal to surface), analysis on thick components. As in XRD, ND as well measures the elastic strain using Bragg's law and calculates the stress with Hooke's law together with elastic modulus (E) and Poisson's ratio (v). Neutron diffraction for residual stress measurements is not widely available and easily accessible due to expensive stationary diffractometers for neutron generation.

Non-destructive measurement depth is about 40 mm for steel and about 50 mm for aluminum. Especially in the aircraft manufacturing industry, neutron diffraction is used as a non-destructive method to investigate the residual stress distribution.

The spatial resolution is not very high in neutron diffraction. It is in the range of millimeters.

Relevant Standards for ND

ISO/TS 21432:2005 Non-destructive testing – Standard test method for determining residual stresses by neutron diffraction

Residual Stress Measurement with Synchrotron Diffraction

Synchrotron diffraction is a higher energy version of X-ray diffraction which provides full residual stress tensor, σ11 (parallel to surface), σ22 (parallel to surface) and σ33 (normal to surface), analysis with even a higher resolution than neutron diffraction. It is possible to use synchrotron diffraction for components with complex geometries but usually the size of the component is limited. There are only number of synchrotron facilities around the world which makes the method not portable and lead time to have the results way too long.

Non-destructive measurement depth is about 25 mm for steel and about 100 mm for aluminum. However, the spatial resolution is not as good as XRD method.

MECHANICAL STRAIN RELAXATION BASED METHODS

ESPI with Hole Drilling

Prism (Precision Real-Time Instrument for Surface Measurement) is a residual stress measurement system developed by Stresstech. Prism is based on three principles: traditional hole drilling, distortion measurement, and residual stress calculation.

Traditional Hole Drilling: Hole drilling removes a volume of material from the workpiece hence changes the stress equilibrium in the part. The remaining material rebalances its stress fields and near the hole the surface distorts slightly.

Distortion Measurement: Prism measures surface distortion optically using a laser light with a technology based on Electronic Speckle Pattern Interferometry (ESPI). The measured surface displacements are correlated with planar stresses.

Residual Stress Calculation: The residual stress calculation requires ESPI images of the measurement surface before and after each drilling increment. This allows the determination of surface displacements as a fraction of the wavelength. The stress calculation algorithm is compatible with the requirements described in the strain-gage hole-drilling ASTM standard.

Prism provides very fast stress depth profile and it requires little sample preparation. The system does not use strain gage which is one of the main disadvantages of the deep hole drilling method. Prism is suitable for measuring many different materials including steels, aluminium, titanium, copper and composites.

Relevant Standards for ESPI with Hole Drilling

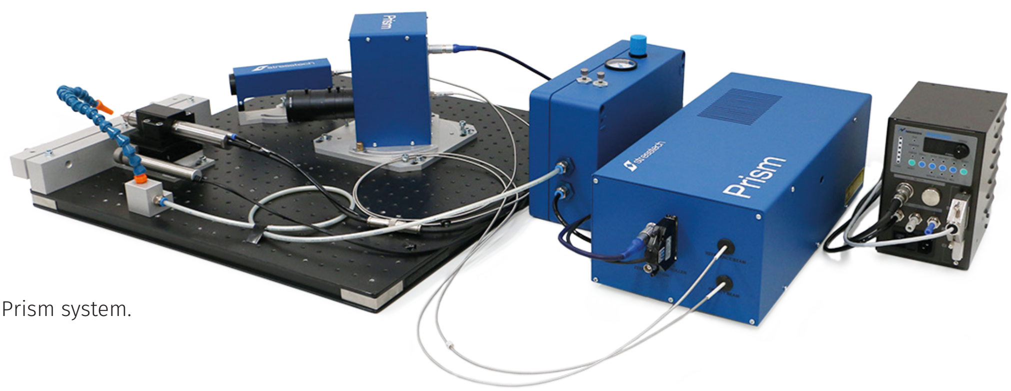
ASTM E837 - 13a Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method

A National Measurement Good Practice Guide, The Measurement of Residual Stresses by the Incremental Hole-Drilling Technique, National Physical Laboratory, UK

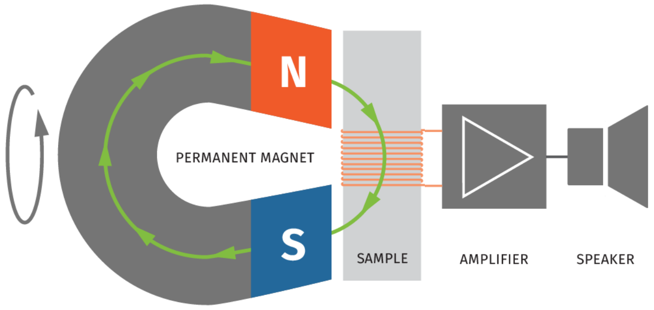
Deep-hole Drilling

Deep-hole Drilling (DHD) method provides bi-axial residual stress measurement for many different material types and even for complex geometries. Semi-destructive measurement depth could be up to 750 mm.

In addition to above methods, incremental center-hole drilling, contour, slitting, block removal, splitting and layering, Sach's boring, inherent strain, ring-core, and indentation are known and used destructive methods for residual stress measurements.



Prism system.



OTHER METHODS

Barkhausen Noise Analysis

Barkhausen Noise Analysis (BNA) is based on a concept of inductive measurement of a noise-like signal, generated when a magnetic field is applied to a ferromagnet.

Two main material characteristics will directly affect the intensity of the Barkhausen noise signal.

The presence and distribution of elastic stresses influence domains to choose and lock into their easy direction of magnetization. This phenomenon of elastic properties interacting with domain structure and magnetic properties of material is called magnetoelastic interaction.

As a result of magnetoelastic interaction, in materials with positive magnetic anisotropy (iron, most steels and cobalt) compressive stresses will decrease the intensity of Barkhausen noise while tensile stresses increase it.

This fact can be exploited so that by measuring the intensity of Barkhausen noise the amount of residual stress can be determined. The measurement also defines the direction of principal stresses.

Processes as cold rolling and shot peening which are used to create complex compressive residual stress distributions at the surface layer can be characterized by Barkhausen noise.

The effective depth of signal penetration is between 0.01 mm and 1 mm.

Relevant Standards for BNA

SAE ARP 4462 - Barkhausen Noise Inspection for Detecting Grinding Burns in High Strength Steel Parts

Ultrasonic

Ultrasonic analysis could be used to determine the stress levels. In this method, time of the ultrasonic wave's flight between the sensor and the transition zone is calculated. The stress calculation is based on velocity measurement of the ultrasonic wave. However, velocity of the ultrasonic waves is also affected by microstructure and defects. There are number of studies and even specifically designed hardware (both laboratory and portable) for ultrasonic measurement of residual stresses. Ultrasonic method offers a non-destructive measurement possibility of 150 mm depth. Calibration of the stress measurement requires a stress free sample which is the disadvantage of this method.

In addition to above methods, photoelastic and thermoelastic are not commonly used non-destructive methods for residual stress measurements.

Stresstech is a research oriented company with more than 30 years' experience in residual stress engineering and stress evaluation. Feel free to contact us to learn more about measurement of residual stresses and their evaluation.

www.stresstech.com

Sources

"Residual Stress Measurement by X-Ray Diffraction", 2003 Edition by SAE International

"6th Residual Stress Workshop" Lecture notes